THE CONTEXT OF HIGH ENERGY QCD SPIN PHYSICS *

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Talk presented at the Adriatico Research Conference
Trends in Collider Spin Physics
ICTP, Trieste, Italy
5 – 7 December 1995
and at the RIKEN Symposium
Spin Structure of the Nucleon
RIKEN, Wako-shi, Saitama, Japan
18 – 20 December 1995

*This work is supported in part by funds provided by the U.S. Department of Energy (D.O.E.) under contracts #DF-FC02-94ER40818 and #DF-FG02-92ER40702 and by the National Science Foundation (N.S.F.) under grant #PHY 92-18167.

MIT-CTP-2518 and HUTP-96/A010 January 1996

As the first speaker I would like to give an broad view of the opportunities to explore QCD at a very high energy polarized hadron collider. The better we understand perturbative QCD the more we are able to use it to probe the still unsolved mysteries of confinement. My central message is that polarized colliders will provide a wealth of new information about the behavior of quarks and gluons inside hadrons complementing that available from lepton scattering and other more familiar probes of hadron structure.

My talk is organized as follows:

1. Introduction
2. Brief Remarks on the g_1 Situation
3. Summaries of Some Issues Related to Polarized Hadron Collider Physics
   - Low Energy Flavor Physics
   - Transverse Spin
   - Higher Twist
4. Future Prospects at Polarized Hadron Colliders
   - $\frac{\mathcal{A}_{TT}}{\mathcal{A}_{LL}}$ — a test of the QCD Parton Formalism
   - A Brief Summary of Some Flagship Experiments

1. Introduction — Precise Probes of Hadron Structure

Light quark QCD looks simple and elegant — an unbroken non-Abelian gauge theory of nearly massless (u, d and s) quarks interacting by with a Lagrangian one can fit on a postage stamp, let alone a T-shirt,

$$\mathcal{L}_{QCD} = -\frac{1}{4}\,\mathrm{Tr}\,\mathbf{F}^2_{\mu\nu} + \bar{q}(i\gamma_\mu \mathbf{D}^\mu + m)q. \tag{1}$$

Hadron phenomena are rich and regular, displaying many features not accounted for by the symmetries of $\mathcal{L}_{QCD}$ alone. Examples include the OZI rule, the $SO(3)\times SU(6)$ classification of baryons, the absence of exotics, and the early onset of asymptotic behavior in form factors and structure functions. We have little fundamental understanding of these apparently simple regularities in terms of the underlying Lagrangian. These regularities fascinate some of us even more than the computation of specific quantities like masses and coupling constants.

Traditional tools for exploring the structure of bound states have only limited usefulness in the relativistic regime of light-quark QCD. Physicists unraveled atomic and nuclear structure by precision studies of i) excitation spectra, ii) electroweak form factors, and iii) quasi-elastic scattering. All three have yielded important information about the structure of hadrons in the past — the study of hadron resonances gave us the quark model, form factor measurements gave the first evidence of hadron compositeness, and quasi-elastic lepton scattering of electrons and neutrinos led to QCD and the quark-parton model. However i) and ii) are considerably less powerful in the relativistic regime than in traditional Schroedinger quantum mechanics.

From form factors we learn the single particle matrix elements of electroweak currents. "Charges" measured at zero momentum transfer include the vector and axial charges of β-decay. Just away from $\vec{q} = 0$ one obtains magnetic moments and charge radii, $\langle r^2 \rangle = -6 \frac{\partial F}{\partial q^2}|_{q^2=0}$, *etc.* The form factor of a non-relativistic system is directly related to the fourier transform of some density in coordinate space. However this connection fails beyond the first term or two in the expansion in q^2, when the Compton wavelength of a system is not negligible compared to its intrinsic size. For atoms and nuclei, $\lambda_c \ll \sqrt{\langle r^2 \rangle}$, but for the nucleon $\lambda_c / \sqrt{\langle r^2 \rangle} \approx 0.25$ and the connection is lost. Despite this limitation, several interesting "charges" remain to be measured. The programs to measure the strangeness radius, axial charge and magnetic moment of the nucleon at CEBAF show the vitality of this tradition, and connect the low energy physics community to the community interested in polarized collider physics.[1]

The interpretation of excitation spectra in QCD is complicated by the fact that quarks and gluons are so light. Even the first excited state of the nucleon, the $\Delta(1232)$, is above particle (pion) emission threshold. The fundamental quanta — quark and gluons — are so light that it is hard to imagine that hadrons are well approximated as states of definite particle number. Instead modern quark models adopt a "quasiparticle" point of view, where "constituent" quarks and gluons are viewed as coherent states of the fundamental quanta which preserve their identity in the hadronic environment. In general, spectra become uninterpretable in any channel beyond the first couple of states. Still there are several fairly precise and very interesting questions in spectroscopy: Where are the "glueballs"? Where are the CP-exotic mesons that cannot be non-relativistic $Q\bar{Q}$–states? Is there a bound or nearly bound dihyperon?

Quasielastic (deep inelastic) scattering from quarks and gluons, and its generalizations to annihilation and hard hadron-hadron collisions are much more important in QCD than in nuclear or atomic physics. In part this is because other tools are less useful, but it also reflects the extraordinary power, precision and flexibility the method attains in QCD. Unlike the nuclear force, QCD simplifies at short distances and the quasielastic approximation (*i.e.* the renormalization group improved parton model) becomes exact at large momentum transfer. Furthermore, corrections to the leading asymptotic behavior (so-called "higher twist" effects) can be classified and analyzed with the same tools. Parton distribution and fragmentation functions appear to be the most useful and abundant information available on the structure of hadrons. Extensions to spin dependent and higher twist effects offer a wealth of new information which can be the testing ground both of phenomenological models of confinement and of numerical simulations.

At present we have accurate information on the momentum distribution of quarks and gluons in the nucleon. We have fairly accurate measurements of the helicity distribution of quarks in the neutron and proton. We know that at $Q^2 = 20$ GeV^2 gluons carry about 43% of the nucleon's momentum, quarks carry about 57%,[2] $\bar{u}$ and $\bar{d}$ quarks carry $13.5 \pm 0.3\%$, and s and $\bar{s}$ quarks carry $4.1 \pm 0.4\%$.[3,4] We know that $\bar{u}$ and $\bar{d}$ quarks are distributed differently within the proton. We know that the fraction of the spin of the nucleon carried on the spin of the quarks is small — the most recent value is about $20 \pm 10\%$ at $Q^2 = 10 GeV^2$. These are examples of the kind of precise information obtained by using perturbative QCD to probe confinement.

In the not too distant future as a result of experimental programs described at this meeting, we can expect to have information on

- the flavor dependence of quark and antiquark helicity distributions,
- the helicity weighted distribution of gluons in a polarized nucleon,
- information on polarized quark-gluon correlation functions from the study of the transverse spin distribution, g_2,
- estimates of the *transversity* weighted distribution of quarks in the nucleon, and
- measurements of spin dependent effects in quark and gluon fragmentation processes.

Experiments and facilities at SLAC, CERN, HERA, and BNL all will contribute to this program. Other experiments at lower energies at CEBAF, Mainz and Bates will provide complementary information on the spin and flavor structure of hadrons.

The primary objects of interest in short distance probes of nucleon structure are quark and gluon distribution functions. Table 1 summarizes all the leading twist (scaling, modulo logarithms) distributions of quarks and gluons in a spin-1/2 target. Some, like the transversity distribution, δq, cannot be measured in conventional deep inelastic scattering and are prime candidates for experiments at polarized hadron colliders. Others like the polarized gluon distribution, ΔG, may be more accessible in polarized hadron colliders than in deep inelastic lepton scattering. The twist three ($\mathcal{O}(1/Q)$, mod logs) distributions listed in Table 2 provide precise probes of quark–gluon correlations in the nucleon. While g_T is most accessible in deep inelastic scattering, h_L may be measured in polarized hadron collisions.

Parton	Spin Average f_1	Helicity Difference g_1	Transversity Difference h_1
Quark	$q(x,Q^2)$	$\Delta q(x,Q^2)^\dagger$	$\delta q(x,Q^2)^\dagger$
Antiquark	$\bar{q}(x,Q^2)$	$\Delta \bar{q}(x,Q^2)^\dagger$	$\delta \bar{q}(x,Q^2)^\dagger$
Gluon	$G(x,Q^2)$	$\Delta G(x,Q^2)^\dagger$	— †

Table 1. Quark, antiquark and gluon distribution functions at leading twist. Those marked with a † are particularly interesting for polarized hadron colliders. Note the absence of a gluon transversity distribution at leading twist.

Parton	Spin Average	Helicity Difference	Transversity Difference
Quark & antiquark	$e(x,Q^2)$	$h_L(x,Q^2)^\dagger$	$g_T(x,Q^2)$

Table 2. Quark and antiquark distributions at twist-three $\mathcal{O}(1/Q)$.

2. Brief Remarks on the g_1 Situation

It is impossible to give a talk on the future prospects for probing the spin structure of hadrons without mentioning the tremendous progress that has been made since the first attempts to measure the deep inelastic spin asymmetry at SLAC in the early 1970's. Fig. 1 shows the data published in 1976 by the SLAC/Yale (E80) collaboration. For comparison Fig. 2 shows a compilation of asymmetry data including recent CERN (SMC) and SLAC (E143) measurements with the old SLAC/Yale (E80/130) data.* A recent compilation of data on g_1 for proton, neutron and deuteron targets is shown in Fig. 3. Such accurate data has allowed experimenters to test the sum rules that relate integrals over data to forward matrix elements of axial charges. These are perhaps the simplest examples of the sort of precise information available from deep inelastic probes.

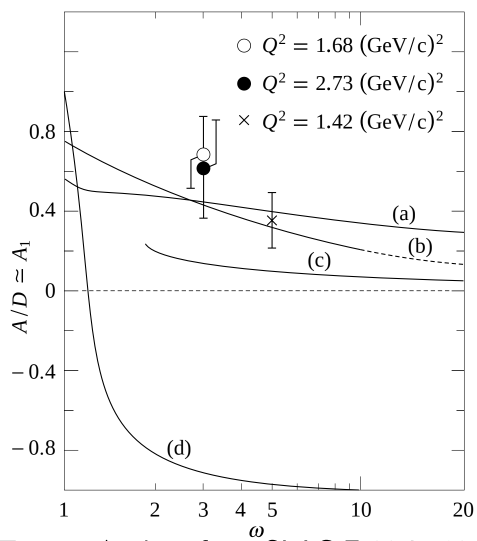

Fig. 1. A_1 data from SLAC E-80 in 1976.

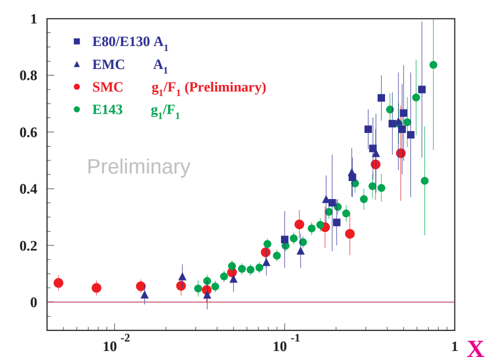

Fig. 2. A recent compilation of data on A_1 from SMC.

The Bjorken Sum Rule follows from isospin symmetry and the short distance analysis of QCD.[5] So firm a dynamical basis has both advantages and disadvantages. On the one hand, the BjSR tests QCD at a very fundamental level. On the other hand, if it is verified, we have learned nothing new about hadron structure. The elementary form of the sum rule reads

$$\int_0^\infty dx g_1^{p-n}(x, Q^2) = \frac{1}{6}\frac{g_A}{g_V}, \tag{2}$$

where $\frac{g_A}{g_V}$ is the ratio of axial vector decay constants measured in $n \to pe^-\nu$. Although I will generally ignore the real complexity that underlies comparison between theory and experiment in QCD, the BjSR provides an opportunity to illustrate the effects that must be taken into account if a reliable comparison is to be made. Three conceptually different types

*Figs. 2, 3 and 4 are copies of the transparencies shown by J. Lichtenstadt at the Trieste Conference. They are preliminary and subject to revision. I am grateful to Dr. Lichtenstadt for copies of his figures.

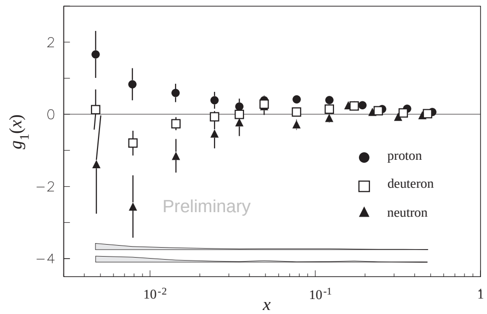

Fig. 3. Data from SMC on g_1 for the proton, neutron and deuteron.

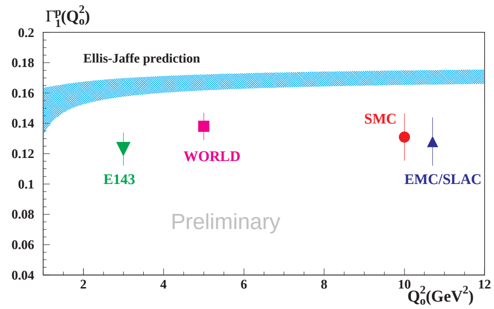

Fig. 4. Comparison of data with the assumption $\Delta s = 0$ from SMC.

of corrections afflict eq. (2): i) perturbative QCD corrections to the leading twist operator — the isovector axial charge; ii) kinematic $\mathcal{O}(\frac{1}{Q^2})$ corrections due to the non-vanishing mass of the target nucleon; and iii) dynamical $\mathcal{O}(\frac{1}{Q^2})$ due to quark-gluon corrections in the nucleon — the so-called higher-twist effects. These replace the original sum rule with,

$$\begin{aligned}\int_0^\infty dx g_1^{p-n}(x,Q^2) &= \frac{1}{6}\frac{g_A}{g_V}\{1-\frac{\alpha_s}{\pi}-\frac{43}{12}\frac{\alpha_s}{\pi}^2-20.215\frac{\alpha_s}{\pi}^3+\ldots\} \\ &+ \frac{M^2}{Q^2}\int_0^1 dx x^2\{\frac{2}{9}g_1^{p-n}(x,Q^2)+\frac{1}{6}g_2^{p-n}(x,Q^2)\} \\ &- \frac{4}{27}\frac{1}{Q^2}\mathcal{F}^{u-d}, \end{aligned} \tag{3}$$

where $\mathcal{F}$ is the invariant matrix element associated with a twist-four operator, $2\mathcal{F}^u S^\sigma = \langle P,S|g\bar{u}\tilde{F}^{\sigma\lambda}\gamma_\lambda u|P,S\rangle$. These corrections complicate the comparison of experiment with theory. On the other hand, if g_1^{p-n} can be measured accurately enough, the magnitude of this quark-gluon correlation within the nucleon can be extracted from experiment.

The separate spin sum rules for the proton and neutron are not as fundamental as the BjSR because they involve an otherwise unknown nucleon axial charge. If we define the light quark axial charges of the proton by $\Delta q(Q^2)S_\alpha = \langle P,S|\bar{q}\gamma_\alpha\gamma_5 q|P,S\rangle$, for $q=u,d,s$, then we can write sum rules for the proton and deuteron (ignoring any bound state corrections for the deuteron),

$$\begin{aligned}\int_0^1 dx g^{ep}(x,Q^2) &= \frac{1}{2}\left(\frac{4}{9}\Delta u(Q^2)+\frac{1}{9}\Delta d(Q^2)+\frac{1}{9}\Delta s(Q^2)\right) \\ &= \frac{1}{18}\left(3F+D+2\Sigma(Q^2)\right)=\frac{1}{18}\left(9F-D+6\Delta s(Q^2)\right) \\ \int_0^1 dx g^{ed}(x,Q^2) &= \frac{1}{2}\left(\frac{5}{9}\Delta u(Q^2)+\frac{5}{9}\Delta d(Q^2)+\frac{2}{9}\Delta s(Q^2)\right) \\ &= \frac{1}{18}\left(3F-D+4\Sigma(Q^2)\right)=\frac{1}{18}\left(15F-5D+12\Delta s(Q^2)\right). \end{aligned} \tag{4}$$

All perturbative QCD, target mass and higher twist corrections have been suppressed in eqs. (4). Two linear combinations of the three light flavor axial charges can be related to

(scale independent) combinations of the axial charges (F and D) measured in hyperon and neutron β–decay. The third, Σ, is the fraction of the spin of the nucleon carried by the spin of the light quarks, and depends on Q^2 because the conservation of the associated axial current is ruined by the axial anomaly.

$$\begin{aligned}
\Delta u(Q^2) - \Delta d(Q^2) &= F + D \\
\Delta u(Q^2) + \Delta d(Q^2) - 2\Delta s(Q^2) &= 3F - D \\
\Delta u(Q^2) + \Delta d(Q^2) + \Delta s(Q^2) &= \Sigma(Q^2)
\end{aligned} \tag{5}$$

These relations assume exact $SU(3)_{\text{flavor}}$ symmetry for octet baryon axial currents, which seems to agree with available data (although see below for further discussion).

When eqs. (4) were first derived, Δs was assumed to vanish.[6] Although this may have been reasonable at the time, we now know that each of the light-flavor axial charges is scale dependent (via the anomaly [7]) so if Δs vanishes at one Q^2 it will not vanish elsewhere. It is interesting to note, nevertheless, that the assumption $\Delta s = 0$ corresponds to $\Sigma = 3F - D$, and with the current values of $F + D = 1.2573 \pm 0.0028$ and $F/D = 0.575 \pm 0.016$ one gets $\Sigma = 0.579 \pm 0.025$. So $SU(3)_{\text{flavor}}$ symmetry and no polarized strange quarks in the nucleon already suggest something peculiar going on with the nucleon spin.[8] This is associated with the failure of the non-relativistic quark model to account for axial charges — *viz.* the famous $g_A/g_V = 5/3$ for neutron β–decay.

Fig. 4 shows a recent compilation of the world's data on the proton sum rule compared with the prediction $\Delta s = 0$. Clearly there is strong evidence that Δs is negative and therefore that Σ is even smaller than anticipated in the quark model. Recent values hover around $\Sigma = 0.2 \pm 0.1$ or, equivalently, $\Delta s = -0.12 \pm 0.04$ using the relation $\Sigma = 3F - D + 3\Delta s$.[9]

There have been many reviews of the issues raised by the unexpectedly small fraction of the spin of the nucleon carried on the spin of the light quarks. For an elementary introduction see Ref. [10]. Here, briefly, are a few comments from a theoretical perspective:

- Theorists have not come up with a "gee whiz" solution, *i.e.* there is no simple and elegant explanation that leaves conventional quark model phenomenology intact and explains the small value of Σ.

- Certain "trivial" effects raised when the data first appeared still plague the interpretation of the data. In particular,

  - Violation of $SU(3)_{flavor}$ symmetry for octet axial charges could affect the evaluation of the sum rules. There has been a recent flurry of activity on this subject.[11–14] Forte has pointed out that the extraction of Σ from the data is relatively insensitive to uncertainties in the less well known combination $3F - D$.[14] However his analysis stays within the parameterization (eq. (5)) given by exact SU(3) and therefore does not bound the effects of SU(3) violation. Refs. [12,13] both claim that SU(3) violation can be sufficient to give $\Delta s = 0$. Direct measurement of Δs in *νp elastic* scattering as proposed at Los Alamos would settle the issue. [15]

– Unanticipated behavior of the functions $xg_1(x,Q^2)$ as $x \to 0$ could affect the sum rules. The latest low–x data from SMC (see Fig. 3) suggest tantalizing deviations from expected behavior — note, for example the increase of g_1^d at the lowest-x. Unfortunately it is hard to obtain much guidance from data with such large error bars.

– No signs of strong, sub-asymptotic Q^2 dependence have been seen at SLAC. The possibility that the early evaluations of the sum rules were contaminated by sub-asymptotic corrections [16,17] that would vanish at higher Q^2 and reveal a larger value of Σ seems less likely as more accurate low Q^2 data and very large Q^2 data become available.[18]

- What does carry the spin of the nucleon? A separation into four terms is often quoted,

$$\frac{1}{2} = \frac{1}{2}\Sigma + \Delta L_Q + \Gamma + \Delta L_G, \tag{6}$$

where ΔL_Q and ΔL_G are the quark and gluon orbital angular momenta, and Γ is the gluon spin. [19] It is not obvious that the total angular momentum can be grouped into the sum of four terms. After all, the energy cannot be written this way because it contains interaction dependent terms that cannot be attributed to quarks or gluons separately. Recently Ji and collaborators have shown that such a separation is both gauge and renormalization scheme dependent.[20] There is a natural definition of Γ as the integral over ΔG,[21] and Ref. [20] argues for particular definitions of ΔL_Q and ΔL_G with interesting consequences (see below). However a definition of ΔL_Q and ΔL_G that makes contact with experiment is still lacking.

Many have speculated that Γ is large and positive in order to make up for the deficiency in Σ.[22] *A priori* not even the sign of Γ is known, and it may be negative.[21] This question can be addressed by experiment since Γ can be defined in terms of an integral over the polarized gluon distribution in the nucleon[21] and can be measured.

- Ji, Tang and Hoodbhoy have studied the Q^2 evolution of the four terms in eq. (6).[20] In light-cone gauge they can use traditional parton model analysis to calculate the GLAP splitting functions necessary to construct evolution equations. Two of their observations are particularly interesting:

– First, they find that the anomalous dimension matrix for the four operators has a zero eigenvalue, with the result that in the *very* large Q^2 limit where all other eigenvectors of the anomalous dimension matrix have evolved to zero, the ratio of quark and gluon contributions goes to a definite limit, independent of hadronic target. This is exactly analogous to the result for the momentum sum rule, and indeed, the numbers are the same:

$$\begin{aligned} \lim_{\ln Q^2\to\infty} \Delta L_Q + \frac{1}{2}\Sigma &= \frac{1}{2}\frac{3N_f}{16+3N_f} \\ \lim_{\ln Q^2\to\infty} \Delta L_G + \Gamma &= \frac{1}{2}\frac{16}{16+3N_f} \end{aligned} \tag{7}$$

The result can be motivated by the observation that the angular momentum density tensor is linearly related to the stress tensor — $M^{\mu\nu\lambda} = x^\nu T^{\mu\lambda} - x^\lambda T^{\mu\nu}$ up to total derivatives. For reasons that have never been well understood, the momentum is partitioned according to this asymptotic result even at relatively low Q^2 — $\frac{\varepsilon_Q}{\varepsilon_G} \approx 1$. If the same is true for the angular momentum then, $\Delta L_Q + \frac{1}{2}\Sigma \approx \frac{1}{4}$ and $\Delta L_G + \Gamma \approx \frac{1}{4}$ even at moderate Q^2. Continuing this speculation to its logical conclusion, we can combine this with the known result that $\Sigma \approx 0.3$ and eq. (6), to obtain, $\frac{1}{2}\Sigma \approx 0.15, \Delta L_Q \approx 0.1$ and $\Gamma + \Delta L_G \approx 0.25$, leaving only the separation between Γ and ΔL_G open to debate. It would be very interesting to find a way to test this speculation.

– Second, they find that they can study either of the two popular ways of regulating the infrared behavior of the quark spin contribution.[23] If they choose the prescription suggested by the operator product expansion, say in $\overline{MS}$ scheme, then they obtain eq. (6) itself. If, however, they use an a scheme in which the gluonic contribution to the quark axial charges arising from the triangle anomaly is explicitly separated out (as, for example, advocated in Refs. [22]), $\Sigma \to \Sigma - \frac{\alpha}{2\pi} N_f \Gamma$, then they find that the quark orbital angular momentum has a compensating gluonic contamination, $\Delta L_Q \to \Delta L_Q + \frac{\alpha}{4\pi} N_f \Gamma$, so that eq. (6) now reads,

$$\frac{1}{2} = \frac{1}{2}\left(\Sigma - \frac{\alpha}{2\pi} N_f \Gamma\right) + \left(\Delta L_Q + \frac{\alpha}{4\pi} N_f \Gamma\right) + \Delta L_G + \Gamma. \tag{8}$$

So the net effect of the renormalization scheme dependence is only to shift a contribution between quark spin and orbital angular momentum.

3. Issues Related to Polarized Hadron Collider Physics

Although the primary motivation for pursuing a program in polarized hadron-hadron physics at a very high energy collider comes from the surprises discovered in polarized deep inelastic scattering, there are several other areas of hadron physics that will contribute to or be affected by such a program. As we discuss the physics opportunities at a polarized hadron collider at this workshop it is important to keep these connections in mind.

3.1. Strange Quarks in the Nucleon

The observation that strange quark matrix elements in the nucleon are larger than expected in the naive quark model began the revival of interest in quark and gluon substructure of hadrons. The current state of affairs is summarized in Table 3. [For data and further discussion on $\varepsilon_s + \varepsilon_{\bar{s}}$ see Ref. [3], on $m_s\langle \bar{s}s\rangle$ see Ref. [24], on ΔS see ref. [25]]

Strange quark matrix elements in the nucleon give us the most precise measures of OZI-Rule violation. Naive quark models exclude strange quarks from the nucleon. Perturbative QCD, dynamical chiral symmetry breaking and non-perturbative models of confinement all introduce $\bar{s}s$ admixtures. Some models, like the $SU(3)_{flavor}$ symmetric Skyrme model go to the opposite extreme from the naive quark model and introduce very large strangeness admixtures into the nucleon. I would like to stress a few points —

Operator	Name	Quarks	Current Value	Comments
$s^\dagger s$	STRANGENESS	$s-\bar{s}$	0	Just an example
$r^2 s^\dagger s$	STRANGE RADIUS $\langle r_s^2\rangle$	$s-\bar{s}$	???	$e^\uparrow p \to ep$
$\bar{s}\gamma^+\partial^+ s$	STRANGENESS MOMENTUM FRACTION $\varepsilon_s+\varepsilon_{\bar{s}}$	$s+\bar{s}$	0.0408 ± 0.0041	$\nu N \to \mu^+\mu^- X$ $\bar{\nu} N \to \mu^+\mu^- X$
$m_s \bar{s}s$	STRANGE SCALAR DENSITY $m_s\langle \bar{s}s\rangle$	$s+\bar{s}$	190 ± 60 MeV	Low energy πN scattering
$\frac{1}{2}\vec{r}\times s^\dagger \vec{\alpha} s$	STRANGE MAGNETIC MOMENT μ_s	$s^\uparrow - s^\downarrow$ $+\bar{s}^\downarrow - \bar{s}^\uparrow$	???	$e^\uparrow p \to ep$
$\bar{s}\vec{\gamma}\gamma_5 s$	STRANGE SPIN FRACTION Δs	$s^\uparrow - s^\downarrow$ $-\bar{s}^\downarrow + \bar{s}^\uparrow$	-0.10 ± 0.03	$e^\uparrow p^\uparrow \to eX$, $\nu N \to \nu N$
$i\bar{s}\sigma^{0i}\gamma_5 s$	STRANGE TENSOR CHARGE δs	$s^\uparrow - \bar{s}^\uparrow$ $-s^\downarrow + \bar{s}^\downarrow$	???	Chiral odd deep inelastic processes

Table 3. Current information on the nucleon matrix elements of $\bar{s}s$ operators.

- The strange quark contribution to the momentum fraction increased significantly a couple of years ago with the realization that a (next to leading order (NLO)) perturbative correction to $\nu p \to \mu^+\mu^- X$ had masked the leading order contribution from $W^+ s \to c$.[4] The abundance of gluons in the nucleon enhances the importance of $W^+ g \to c\bar{s}$. The old analysis of the strange quark momentum fraction, which gave a value around 2.6%, omitted a negative NLO contribution from $W^+ g$ fusion which masks an even larger strange quark fraction.

- It has long been hoped that the right model of "constituent" quarks, superpositions of the "current" quarks that are measured in electroweak processes, could account for the main features of OZI rule violation. Constituent quarks, Q, would be superpositions of current quarks, $\bar{q}q$ pairs, and gluons. Different dynamical pictures of the transformation from q to Q suggest different strangeness mixing patterns. Consider the $m_s = 0$ limit. Perturbative QCD would suggest,

$$u \to u(\bar{u}u + \bar{d}d + \bar{s}s)^n \Rightarrow U, \tag{9}$$

etc. because pairs created by gluons are flavor singlets. A non-perturbative redefinition of the quark fields occurs at the scale of chiral symmetry breaking. The flavor structure of constituent quarks can depend on the dynamics that drives that transition. In the Nambu-Jona Lasinio model of chiral symmetry breakdown through $\bar{q}q\bar{q}q$ operators each

quark flavor mixes only with its own type,

$$u \rightarrow u(\bar{u}u)^n \Rightarrow U, \tag{10}$$

etc. because $SU(3)$ symmetric four quark operators only involve one flavor. On the other hand anomaly (or instanton) induced dynamical chiral symmetry breakdown gives

$$u \rightarrow u(\bar{d}d\bar{s}s)^n \Rightarrow U, \tag{11}$$

because of the determinental character of the 't Hooft interaction.[26] Can the study of nucleon strange quark matrix elements establish the usefulness of the notion of a current→constituent transformation and help decide the dynamical mechanism behind it?

- An impressive list of experiments are underway to probe strangeness matrix elements not yet measured. For a thorough discussion and references to the original proposals see the review in Ref. [1]. Here is a short list —
  - LSND underway at Los Alamos hopes to measure Δs via the axial coupling of the Z^0 in quasielastic $\nu p \rightarrow \nu p$ and $\nu n \rightarrow \nu n$ from carbon nuclei.
  - SAMPLE underway at Bates expects to get a sensitivity of ± 0.2 in μ_s by measuring A_{LR} in $\vec{e}p \rightarrow ep$ and $\vec{e}d \rightarrow ed$ at $E_e = 200 MeV$.
  - At least three experiments being developed at CEBAF: In Hall-A, E91-010 plans a 5% measurement of A_{LR} in $\vec{e}p \rightarrow ep$ at the level of 2×10^{-5}, seeking to measure both μ_s and $\langle r_s^2 \rangle$. In Hall-C, E91-017 plans an approximately 5% measurement of the combination $G_E^{(s)} + G_E^n + 0.2 G_M^{(s)}$ at forward angles using $\vec{e}p \rightarrow ep$ and $\vec{e}d \rightarrow ed$. At backward angles the same experiment plans to separate $G_E^{(s)}$ and $G_M^{(s)}$ at larger momentum transfer. Also in Hall-A, E91-004 plans to study A_{LR} in $\vec{e}\ {}^4He \rightarrow e\ {}^4He$ at $Q^2 \approx 0.6 GeV^2$. Spinless ${}^4He$ removes magnetic and axial vector effects. The experiment should be sensitive to $\langle r_s^2 \rangle$. With $\langle r_s^2 \rangle = 0$, $A_{LR} \approx 5 \times 10^{-5}$. The experiment aims for a sensitivity of 30% of this value.
  - Proposal A4/1-93 for the Mainz electron accelerator aims to measure $\langle r_s^2 \rangle$ via A_{LR} in $\vec{e}p \rightarrow ep$ at $E_e = 855 MeV$.
  - Finally, both the SMC group at CERN and Hermes at HERA plan to try to separate quark flavor contributions g_1 making use of fragmentation triggers.[27] A draft of early SMC results has already appeared. [28]

  With time a more complete picture of the strangeness contamination of the nucleon seems destined to emerge from this wide range of efforts at many laboratories.

3.2. Transverse Spin

Today's excitement about polarized hadronic collider physics is intimately connected with the revival of interest in transverse polarization effects in deep inelastic processes. In the early days of QCD when only deep inelastic lepton scattering (DIS) had been studied

in detail, longitudinal and transverse polarization effects were thought to be quite different. [29] Longitudinal asymmetries in DIS are described by the twist-two (scaling) structure function g_1, while transverse asymmetries measure the twist-three ($\mathcal{O}(1/\sqrt{Q^2})$) structure function g_2. Twist-three structure functions are interaction dependent, and do not have simple parton interpretations. This led to the erroneous impression that transverse spin effects were inextricably associated with off-shellness, transverse momentum and/or quark-gluon interactions. Now we understand that there is a twist-two quark distribution, $h_1(x, Q^2)$, describing transverse spin effects,[30] that it decouples from DIS due to a chirality selection rule of perturbative QCD, and that it dominates transverse asymmetries in certain hard processes such as Drell-Yan production of lepton pairs.[31–33] The correspondence between longitudinal and transverse spin effects is completed by a twist-three, longitudinal structure function, $h_2(x, Q^2)$, analogous to g_2. The correspondence is summarized in Table 4.

	Longitudinal Polarization	Transverse Polarization
Twist-2	$g_1(x, Q^2)$	$h_1(x, Q^2)$
Twist-3	$h_2(x, Q^2)$	$g_2(x, Q^2)$

Table 4. The transverse and longitudinal distribution functions through twist-three.

Experiments to measure h_1 include Drell-Yan with transversely polarized target and beam — $\vec{p}_\perp \vec{p}_\perp \rightarrow \bar{\ell}\ell + X$, [30,32] direct photon and jet production at large $p_\perp$ — $\vec{p}_\perp \vec{p}_\perp \rightarrow \begin{pmatrix} jj \\ j\gamma \end{pmatrix} + X$,[34,35] and inclusive pion or lambda production in deep inelastic scattering — $\vec{e}\vec{p}_\perp \rightarrow \begin{pmatrix} \Lambda \\ \pi \end{pmatrix} + X$.[31,36]

As yet relatively little is known about the properties of h_1. Here is a brief summary. More detail can be found in Ref. [37]

- h_1 measures the probability to find transversely polarized quarks (along, say $\hat{x}$) in a transversely polarized nucleon moving in the $\hat{z}$ direction — known, for brevity, as "transversity".

- For non-relativistic dynamics $h_1 = g_1$, so the difference is a measure of relativistic effects.

- h_1, g_1 and f_1 obey inequalities, $|h_1(x, Q^2)| \leq f_1(x, Q^2)$, $|g_1(x, Q^2)| \leq f_1(x, Q^2)$, and $f_1(x, Q^2) + g_1(x, Q^2) \geq 2|h_1(x, Q^2)|$ for each flavor of quark and antiquark. The last was recently suggested by Soffer.[38] It is only approximately true, since it suffers radiative corrections.[39,40]

- Model calculations suggest that h_1 is of the same order as g_1.[36,41]

- h_1 is related to "tensor operators" in the same sense as g_1 is related to axial vector operators. In particular, the lowest moment of h_1 obeys a simple sum rule,[32]

$$2S^j \delta q^a(Q^2) \equiv \langle P, S|\bar{q}^a i\sigma^{0j}\gamma_5 q^a|_{Q^2}|P, S\rangle \text{and}$$

$$\delta q^a(Q^2) \quad = \quad \int_0^1 dx(h_1^a(x,Q^2) - \bar{h}_1^a(x,Q^2)) \tag{12}$$

for each quark flavor, a.

- There is no gluon analog for h_1. This has interesting consequences for ratios of transverse to longitudinal asymmetries in polarized hadronic processes. We save that discussion for the §4.

3.3. Higher Twist

Higher twist is the generic name for $\mathcal{O}(1/Q^n)$ corrections to deep inelastic processes. If corrections to DIS and other hard processes could be measured precisely enough as functions of x and Q^2 it would be possible to map out interesting quark-quark and quark-gluon correlations within the nucleon. Although interest in higher twist effects has persisted since the mid '70's, theoretical and experimental difficulties have frustrated efforts to measure and interpret them. A major difficulty is that in spin-average deep inelastic scattering or annihilation corrections start at $\mathcal{O}(1/Q^2)$ and these effects are always buried beneath dominant, scaling contributions.[42,43] In addition, target mass corrections $\propto M^2/Q^2$ also have to be removed to expose higher twist. In order to isolate higher twist contributions to F_2 for example, it is necessary first to fit the leading twist contribution which varies like $(\ln Q^2)^\gamma$ in leading order and subtract it away. Next target mass corrections must be fit and subtracted away. Small inaccuracies in the subtraction procedure can mimic higher twist corrections.

One searches for higher twist at low-Q^2 where the corrections are large. However perturbative corrections to leading twist also vary rapidly at low-Q^2 and the two cannot easily be distinguished. Mueller, in particular, has emphasized the ambiguity between higher twist and higher order radiative corrections to leading twist.[44] Consider, for example, a twist-four contribution ($\propto \mu^2/Q^2$) in comparison with a perturbative correction to leading twist $\propto (\alpha/\pi)^n$. The two are indistinguishable over a small Q^2 interval when $\left[\frac{d}{d\ln Q^2}\frac{\mu^2}{Q^2}\right]/\frac{\mu^2}{Q^2} \approx \frac{d}{d\ln Q^2}(\frac{\alpha}{\pi})^n/\frac{\alpha}{\pi}$, or $\frac{9n\alpha}{4\pi} \approx 1$ The question of how to distinguish higher twist from higher order corrections to leading twist is still unresolved.

Spin dependent effects provide an apparently unique reprieve from this complexity. For certain spin dependent observables, it is possible *kinematically* to eliminate leading twist so that a higher twist structure (or fragmentation) function dominates and does not have to be extracted as a correction. The classic example is g_2. If the polarized target in DIS is aligned at exactly 90° to the lepton beam then the cross section is suppressed by $1/\sqrt{Q^2}$ relative to any other polarization direction, and the leading behavior measures the twist three structure function g_2. g_2 and h_2 seem to be unique in this regard. g_2 dominates $\vec{e}\vec{p}_\perp \to e + X$, while h_2 contributes dominantly to $\vec{p}_\| \, \vec{p}_\perp \to \ell^+\ell^- + X$.

The twist-three, transverse spin structure function, g_2, deserves special attention because the first experimental data on g_2 have just been published.[45,46] A more extensive review of the properties and puzzles of g_2 can be found in Ref.[47]. Here is a brief summary of its most interesting features.

- g_2 consists of two pieces, one is a kinematic reflection of g_1 first noted by Wandzura

and Wilczek.[48]

$$g_2(x, Q^2) \equiv g_{2WW}(x, Q^2) + \bar{g}_2(x, Q^2), \tag{13}$$

where

$$g_{2WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2) \tag{14}$$

and $\bar{g}_2$ is the true twist three part of g_2.

- $\bar{g}_2$ measures quark-gluon correlations in the nucleon. It's moments are related to specific local quark-gluon operator products, such as

$$\int_0^1 x^2 \bar{g}_2(x, Q^2) \propto \langle P, S | \frac{1}{8} g \mathcal{S}_{\mu_1\mu_2} \bar{\psi} \tilde{G}_{\sigma\mu_1} \gamma_{\mu_2} \psi | P, S \rangle. \tag{15}$$

Model builders or lattice enthusiasts who want to predict g_2 must confront such matrix elements. In other formulations of higher twist physics, $\bar{g}_2$ can appear to depend on quark transverse momentum.[49] These different expressions are equivalent to eq. (15) by use of the QCD equations of motion, although the form may lead model builders in different directions.

- g_2 obeys an interesting sum rule first derived by Burkhardt and Cottingham,[50]

$$\int_0^1 dx g_2(x, Q^2) = 0 \tag{16}$$

The sum rule is a consequence of rotation invariance and an assumption about the good high energy behavior of Compton amplitudes. It is easily derived from consideration of the bilocal operator matrix element that defines g_1 and $g_T \equiv g_1 + g_2$,[37,51]

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle PS | \bar{\psi}(0) \gamma_\mu \gamma_5 \psi(\lambda n) | PS \right\rangle = 2 \left\{ g_1(x) p_\mu S \cdot n + g_T(x) S_{\perp\mu} + M^2 g_3(x) n_\mu S \cdot n \right\}. \tag{17}$$

If we work in the rest frame, integrate over x and take $\vec{S} \| \hat{e}_3$ and $\mu = 3$, we find $\int\limits_{-1}^{1} dx g_1(x, Q^2) = \langle P\hat{e}_3 | \bar{q}(0) \gamma^3 \gamma_5 q(0)|_{Q^2} | P\hat{e}_3 \rangle$. Next repeat the process with $\vec{S} \parallel \hat{e}_1$ and $\mu = 1$, with the result, $\int\limits_{-1}^{1} dx g_T(x, Q^2) = \langle P\hat{e}_1 | \bar{q}(0) \gamma^1 \gamma_5 q(0)|_{Q^2} | P\hat{e}_1 \rangle$. The right hand sides of these two equations are equal in the rest frame by rotation invariance, whence the sum rule, apparently a consequence of rotation invariance. The subtlety in this derivation is that the integral goes from -1 to 1 including $x = 0$. $g_2(x, Q^2)$ is the limit of a function of Q^2 and ν and therefore might contain a distribution (δ–functions, *etc.*) at $x = 0$. Since experimenters cannot reach $x = 0$, the BC sum rule reads

$$\int_0^1 dx g_2^{\text{observable}}(x, Q^2) = -\frac{1}{2} c, \tag{18}$$

where c is the coefficient of the δ-function. This pathology is not as arbitrary as it looks. Instead it is an example of a disease known as a *"$J = 0$ fixed pole with non-polynomial residue"*. First studied in Regge theory,[52,53] a $\delta(x)$ in $g_2(x, Q^2)$ corresponds to a *real*

constant term in a spin flip Compton amplitude which persists to high energy. There is no fundamental reason to exclude such a constant. On the other hand the sum rule is known to be satisfied in QCD perturbation theory through order $O(g^2)$. The sum rule has been studied by several groups who find no evidence for a $\delta(x)$ in perturbative QCD.[54] So at least provisionally, we must regard this as a reliable sum rule. At least one other sum rule of interest experimentally, the Gerasimov, Drell, Hearn Sum Rule for spin dependent Compton scattering has the same potential pathology. For further discussion of the BC sum rule see Ref. [47]

- It has taken a long time to figure out the evolution of twist three structure functions such as g_2. The subject is too complex and too theoretical to be covered here. The interested reader can find a review in Ref. [37] and in recent talks by Kodaira and Uematsu.[55] Roughly speaking, knowing g_2 as a function of x at a given Q^2 is not sufficient to determine it at larger Q^2. There are a couple of distribution functions of two momentum fractions, x and y, $G(x,y,Q^2)$ and $\tilde{G}(x,y,Q^2)$, which evolve in the standard fashion with GLAP splitting functions, *etc.* G and $\tilde{G}$ probe correlated quark-gluon distributions in an infinite momentum frame. g_2 is obtained from G and $\tilde{G}$ by integrating out the y dependence, but this integrates out information necessary for evolution. Several years ago Ali, Braun and Hiller[56] pointed out that these problems are less severe at large N_c and large x, and more recently, Strattmann[57] used their methods to evolve bag predictions for g_2[51] to large enough Q^2 to compare with data.

- Model predictions for the lowest non-trivial moment of g_2, eq. (15) differ significantly in sign and magnitude.[51,58]

Early data on g_2 provided only upper limits. The E143 Collaboration at SLAC recently published the first non-zero measurements, shown in Fig. (5). This looks like the beginning of a significant program in twist three physics.

4. Physics Prospects at Polarized Hadron Colliders

Nucleon spin and flavor physics has become a major focus of particle and nuclear physics programs. The physics issues outlined in the previous section can be addressed at ongoing and planned experiments at CERN (HMC studying $\vec{\mu}\vec{N} \to \mu h X$), SLAC (the E150's studying $\vec{e}\vec{N} \to eX$), HERA (Hermes studying $\vec{e}\vec{N} \to eX$, $\vec{e}\vec{N} \to ehX$, and $\vec{e}\vec{A} \to eX$) and CEBAF (the many experiments studying $\vec{e}\vec{p} \to ep$). Other more speculative proposals abound. These include a dedicated European electron facility (ELFE), proposals to polarize the main injector at Fermilab and the proton ring at HERA. There are so many possibilities to discuss — they will dominate the program of this workshop — that I will restrict myself to a few that are particularly well matched to a polarized hadron collider, and contrast them with experiments seeking the same information at some of the other facilities listed above.

The list of *desiderata*, particularly well suited to hadron colliders includes measurements of the longitudinal polarization asymmetries, ΔG, $\Delta\bar{u}$, $\Delta\bar{d}$, Δu and Δd, and the transversity distribution, h_1.

There are good, specific reasons to turn to polarized colliders as a source of new information on hadron structure.

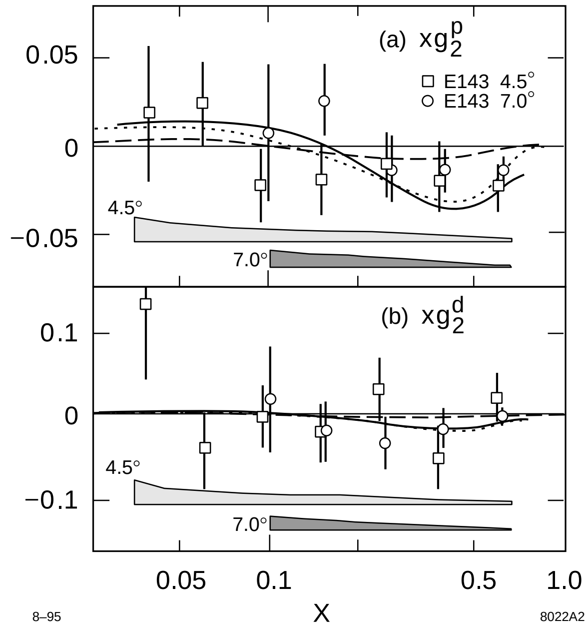

Fig. 5. SLAC E-143 data on g_2.

- First, chiral odd processes are not excluded, so quark transversity distributions can be measured.
- Second, a greater diversity of flavor probes is available. Drell-Yan processes with weak bosons such as $\vec{p}\vec{p} \to Z^0 + X \to \ell\bar{\ell} + X$ and $\vec{p}\vec{p} \to W^\pm + X \to \ell\bar{\ell} + X$ complement $\vec{p}\vec{p} \to \gamma + X \to \ell\bar{\ell} + X$ and provide flavor information that would require the unrealizable process $\nu\vec{p} \to \begin{pmatrix} \mu \\ \nu \end{pmatrix} + X$ in the lepton-hadron scattering domain.
- Finally, it is easier to exploit the gluon-gluon and quark-gluon coupling to obtain information about polarized gluon distributions. Gluons do not couple to leading order in deep inelastic lepton scattering. They appear either through evolution or in higher order processes like heavy quark pair or two jet production. In a polarized hadron collider polarized gluons should dominate the most copious hard processes like two jet production.

4.1. Transverse Versus Longitudinal Asymmetries — A Test of the QCD Parton Formalism

Sometimes we are so busy looking for ways to measure small and interesting effects that we neglect the obvious: *Transverse asymmetries in deep inelastic hadron-hadron collisions (with the important exception of Drell-Yan processes) are extraordinarily small because there is no gluon transversity distribution at leading twist,*

$$\frac{\mathcal{A}_{TT}}{\mathcal{A}_{LL}} \ll 1 \tag{19}$$

for processes such as $pp \to jj + X$, $pp \to \gamma j + X$, $pp \to \pi(k_\perp) + X$, *etc.* ($\pi(k_\perp)$ denotes a pion produced at large $k_\perp$).[34,35]

The argument for this suppression involves the following steps.

- $\mathcal{A}_{TT}$ measures products of parton transversity distributions times fundamental parton-parton scattering cross sections.

- $gq \to gq$ and $gg \to gg/q\bar{q}$ dominate jet production in hadron-hadron collisions except at very large z.

- There is no gluon transversity distribution at twist-two. The transversity distribution is the imaginary part of helicity flip parton-nucleon forward scattering. Leading twist gluons have helicity ± 1, and cannot flip their helicity (Δ helicity $= \pm 2$) scattering forward from a nucleon which can only absorb Δ helicity $= \pm 1$. So gluons decouple from transverse asymmetries. On the other hand,

- There is every reason to expect a significant polarized gluon distribution in the nucleon ($\Delta G \approx G$), so longitudinal asymmetries in jet production should not be small.

- Of the terms that might be large only $qq \to qq$ remains. However it has long been known that this contribution to $\mathcal{A}_{TT}$ is suppressed by a color exchange factor of $\sim \frac{1}{11}$.[59,34]

The ratio $\frac{\mathcal{A}_{TT}}{\mathcal{A}_{LL}}$ is likely to be so small that it will not be observed until polarized hadron colliders have run for many years. Detailed predictions for specific processes will soon be available.[35]

This prediction tests the whole parton spin formalism. In the days before the discovery of h_1, g_2 was believed to be the distribution function relevant to transverse asymmetries. Since gluons *do* couple to g_2 there would be no reason for $\mathcal{A}_{TT}$ to be suppressed. Indeed, the first paper to discuss suppression of $\mathcal{A}_{TT}$,[59] uses g_2, includes gluons, and drops them later, presumably under the assumption that gluons are not polarized.

It is interesting to contrast polarized Drell-Yan processes such as $\vec{p}\vec{p} \to \ell\bar{\ell} + X$ which must proceed in leading order by $\bar{q}q$ annihilation to leading order. In this case gluons do not participate in either the transverse or longitudinal asymmetry. So $\left[\frac{\mathcal{A}_{TT}}{\mathcal{A}_{LL}}\right]_{DY} \approx 1$ unless the quark or antiquark transversity distributions are small compared to their helicity distributions.

This selection rule can only be tested at a polarized hadron collider. It is relatively independent of beam polarizations (which are hard to measure absolutely), and experimental acceptances. It should be a high priority.

4.2. A Brief Summary of Some Flagship Experiments

Much of this Workshop will be devoted to the introduction and study of a few flagship experiments at a high energy polarized collider. I will only list them and their competition at other facilities, leaving the full presentations to later speakers.

4.2.1. ΔG

The measurement of the polarized gluon distribution in the nucleon is perhaps the most important immediate goal in all of hadron spin physics. Because hadrons contain a lot of

glue, polarized hadron collisions are a natural place to look for the effects of ΔG. Two processes look promising: $\vec{p}\vec{p} \to \gamma + \text{jet}$ and $\vec{p}\vec{p} \to 2\text{jets}$. The contributing graphs in leading order are all variants of QCD Compton scattering and they measure either $\Delta G \otimes \Delta q$ or $\Delta G \otimes \Delta G$. Good jet reconstruction and good electromagnetic calorimetry are priorities.

Competition from other regimes include careful evolution studies of $g_1^{eN}(x, Q^2)$ and electroproduction of $\bar{c}c$ pairs. Gluons do not couple directly into deep inelastic scattering but they effect the evolution of the quark distribution via the GLAP equations. Schematically,

$$\frac{d}{d\ln Q^2}\, g_1^{eN} \propto \frac{\alpha_s}{\pi}\{\mathcal{P}_{QQ} \otimes g_1^{eN} + \mathcal{P}_{QG} \otimes \Delta G\}. \tag{20}$$

Sufficiently accurate measurements of the Q^2 dependence of g_1^{eN} should allow the extraction of $\Delta G(x, Q^2)$. Indeed some workers believe they see evidence of a large positive ΔG in existing data.[60] One difficulty of this method is its scheme dependence: there are perfectly reasonable schemes (like $\overline{MS}$) where the integrated ΔG decouples from deep inelastic scattering and GLAP evolution. The $\bar{c}c$ option, first proposed by Carlitz, Collins and Mueller,[22] is based on photon–gluon fusion and could be attempted at electron facilities.

4.2.2. $\Delta\bar{q}$

If one accepts the now standard analysis of CERN and SLAC data, then antiquarks are probably, but not certainly, polarized. Consider, for example, strange quarks. We know that the nucleon contains both s and $\bar{s}$ quarks (*e.g.* from $\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix} p \to \mu^+\mu^- X$), and we know that $\Delta s + \Delta\bar{s} \neq 0$. [For the moment we use Δq and $\Delta\bar{q}$ to refer to the helicity asymmetry of quarks and antiquarks respectively.] Still, this is not enough to prove that $\Delta\bar{s} \neq 0$. Neutrino scattering from polarized targets is out of the question, but the analog Drell-Yan process is a natural goal for a polarized hadron collider. Consider $\vec{p}p \to W^\pm + X$, a parity violating process that proceeds dominantly via $u\bar{d} \to W^+$ or $d\bar{u} \to W^-$. In the parton model,

$$\mathcal{A}_L^+ \sim \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \tag{21}$$

for W^+ and similarly for W^-. The interpretation is cleanest at large x_2 where $\mathcal{A}_L^+ \Rightarrow \Delta\bar{d}(x_1)/\bar{d}(x_1)$. A detector with good lepton, jet and missing transverse energy detection can make an accurate measurement of $\Delta\bar{d}/\bar{d}$ and $\Delta\bar{u}/\bar{u}$.

Competition comes mainly from the use of flavor triggers to identify the scattered quark in deep inelastic electron scattering, $\vec{e}\vec{p} \to e + \{\pi^\pm, \pi^0, K^\pm\} + X$. Such studies will be undertaken by HMC (a successor to SMC at CERN) and by Hermes at HERA, but difficulties separating current and target fragments, and the unknown efficiency of flavor tagging via fragmentation will make this a difficult exercise.

4.2.3. Δq

Clearly, quark helicity distributions can be extracted at the other kinematic limit of eq. (21), when x_1 is large and x_2 is near zero. Then $\mathcal{A}_L^+ \sim \Delta u(x_1)/u(x_1)$. Once again competition appears to be limited to flavor tagging experiments at electron (or muon) facilities.

4.2.4. Transversity

Polarized hadron colliders offer the possibility of measuring the nucleon's third (and final) twist two quark-parton distribution, the transversity, $\delta q(x, Q^2)$. It will not be easy. Transversity effects in two jet production and γ plus jet are very small. Drell-Yan looks better but requires non-vanishing *anti*–quark transversity, $\delta\bar{q} \neq 0$. Although the process is clean in theory, it makes heavy demands on detectors (lepton identification, large acceptance, ...) and accelerator (high luminosity, high polarization, good polarimetry) and will not be the first measurement made at a high energy polarized collider. The prospects for measuring transversities at other facilities are also challenging. I know of three classes of proposals: (1) $\vec{e}\vec{p}_\perp \to e'\vec{\Lambda}_\perp X$, where the self-analyzing decay of the Λ allows extraction of the product of the nucleon transversity multiplied by an analogous Λ–fragmentation function.[31] A particular shortcoming of this proposal is that only strange quarks are likely to have a strong transversity correlation between the target nucleon and the Λ. (2) $\vec{e}\vec{p}_\perp \to e'\pi\pi X$, where the pions are used to construct a jet variable correlating with the target transversity distribution. Our lack of understanding of the analyzing power of the multipion jet fragmentation process complicates this method. (3) Finally $\vec{e}\vec{p}_\perp \to e'\pi X$ has no leading twist asymmetry at all.[32] At twist three there are two contributions, one of which is proportional to the target transversity times a twist three, spin average pion fragmentation function. A lot of unraveling would be required to extract transversity distributions from this process. It could be undertaken at HMC and Hermes.

The prospects for each of these projects at a high energy polarized collider will be discussed in much more detail later in this Workshop.

5. Acknowledgments

I would like to that X. Ji, N. Saito, and M. Tannenbaum for discussions relating to this work.

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